

THE PHYSICAL CONDITIONS OF A LENSED STAR-FORMING GALAXY AT $Z=1.7$

J. R. RIGBY^{1,2}, E. WUYTS^{3,4}, M. D. GLADDERS^{3,4}, K. SHARON⁴, AND G. D. BECKER⁵

ApJ in press

ABSTRACT

We report rest-frame optical Keck/NIRSPEC spectroscopy of the bright lensed galaxy RCGA 032727-132609 at $z=1.7037$. From precise measurements of the nebular lines, we infer a number of physical properties: redshift, extinction, star formation rate, ionization parameter, electron density, electron temperature, oxygen abundance, and N/O, Ne/O, and Ar/O abundance ratios. The limit on [O III] 4363 Å tightly constrains the oxygen abundance via the “direct” or T_e method, for the first time in an average-metallicity galaxy at $z\sim 2$. We compare this result to several standard “bright-line” O abundance diagnostics, thereby testing these empirically-calibrated diagnostics *in situ*. Finally, we explore the positions of lensed and unlensed galaxies in standard diagnostic diagrams, and explore the diversity of ionization conditions and mass-metallicity ratios at $z=2$.

Subject headings: galaxies: high-redshift—galaxies: evolution—gravitational lensing

1. INTRODUCTION

Our knowledge of the Universe’s star formation history has advanced remarkably in the past dozen years. First rest-UV photometry (Madau et al. 1996, 1998), then 24 μ m Spitzer photometry for $0 < z < 2$ galaxies (Caputi et al. 2007; Le Floc’h et al. 2005) and rest-UV photometry at higher redshift (c.f. Ouchi et al. 2009; Bouwens et al. 2010), has shown us that the SFR rises steeply from $z=0$ to $z=1$, has a broad plateau from $z=1$ to $z=4$ –5, and falls off (with debated slope) out to reionization. Thus, the question, “What is the star formation history of the Universe?” has been answered reasonably, and the focus has shifted toward, “Which galaxies formed their stars when, and why, and how did that star-formation change those galaxies and their environments?”

While we have identified the galaxies that formed most of the Universe’s stars, we have much to learn about how that process occurred. One key question is, what were the physical conditions inside these galaxies—metallicity, abundance, extinction, stellar effective temperature, electron temperature and density—compared to star-forming galaxies today? How did these physical conditions evolve through episodes of star formation and gas accretion?

Until the era of extremely large telescopes arrives, our best chance to address this question is to study galaxies that are highly magnified by gravitational lensing. In such rare cases, magnification factors of 20–30 make diagnostic spectroscopy possible with current telescopes. Such work was pioneered in the galaxy MS1512-cB58 (Yee et al. 1996; hereafter cB58) by Pettini et al. (2000)

and Teplitz et al. (2000), and can now be extended to a larger sample thanks to discoveries of bright lensed galaxies (e.g., Allam et al. 2007; Belokurov et al. 2007; Smail et al. 2007; Rigby et al. 2008; Koester et al. 2010.)

Among these new discoveries is RCGA 032727-132609, hereafter RCS0327, at $z=1.7$ (Wuyts et al. 2010), discovered from the second Red Sequence Cluster Survey (RCS2; Gilbank et al. in prep.). With an integrated g -band magnitude of 19.15, we believe RCS0327 to be the brightest high-redshift lensed galaxy yet found. Wuyts et al. (2010) present the discovery, spectroscopic confirmation, deep-follow-up imaging, spectral energy distribution modeling, and preliminary lensing analysis. In this paper, using 1.3 hr of integration with NIRSPEC on Keck, we determine with unprecedented precision the physical conditions of star formation in this hopefully-typical galaxy at the crucial epoch of $z\sim 2$.

2. METHODS

RCS0327 was observed on 04 Feb. 2010 UT with the NIRSPEC spectrograph (McLean et al. 1998) on the Keck II telescope. The weather was clear, and the seeing was measured as 0.85” and 0.45” when the telescope was focused during the night. We used the low-resolution mode and the 0.76” \times 42” longslit. We targeted the brightest $\sim 10''$ of the arc, at a position angle of 134°, as shown in Figure 1. The target was acquired by offsetting from nearby stars on the near-IR slit-viewing camera, target acquisition was verified by direct imaging on this camera. The target was nodded along the slit in an AB pattern, with exposures of 600 s per nod. Table 1 summarizes the filters and exposure times. The A0V star HD 23683 was observed every hour as a telluric standard.

We reduced the spectra using the *nirspec_reduce* package written by one of us (G. D. Becker), which uses lamp exposures to flatten the data, the sky lines to wavelength calibrate, and optimally fits and subtracts the sky following Kelson (2003). For each frame, we measured the spatial profile of the lensed arc by fitting the brightest emission lines, then used this spatial profile to optimally extract the spectrum.

The arc is extended over 38”, roughly 10” of which was captured by the NIRSPEC slit. In a subsequent

Jane.R.Rigby@nasa.gov

¹ NASA Goddard Space Flight Center, Code 665, Greenbelt MD 20771

² Previous: Carnegie Fellow, Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101

³ Department of Astronomy & Astrophysics, The University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637

⁴ Kavli Institute for Cosmological Physics, University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637

⁵ KICC Fellow, Kavli Institute for Cosmology, Cambridge England

Table 1
Observation Log

filter	t(s)	wavelength range(μm)
NIRSPEC-1	1200	0.948–1.16
NIRSPEC-3	2400	1.14–1.43
NIRSPEC-6	1200	1.76–2.19

paper, we will analyze the spatial variation of physical conditions across the arc. In this paper, we consider the integrated spectrum.

Each extracted spectrum was corrected for telluric absorption and fluxed using the tool *xtellcor_general* (Vacca et al. 2003), using the closest-in-time observation of the AOV standard star. The flux level is thus appropriate for the fraction of the galaxy inside the slit, not for the whole galaxy. In §3.3 we estimate the factor by which our NIRSPEC fluxes should be scaled to represent the whole galaxy.

Using a telluric standard to flux the spectra provides excellent relative fluxing within a given filter, but because observations were taken in three separate filters, there can be offsets between filters due to differential slit losses, due for example to changes in seeing or pointing. In addition, the lines in filter NIRSPEC-6 are observed right at the edge of an atmospheric transmission window, and thus may suffer especially high telluric variability. We address these issues in §3.2.

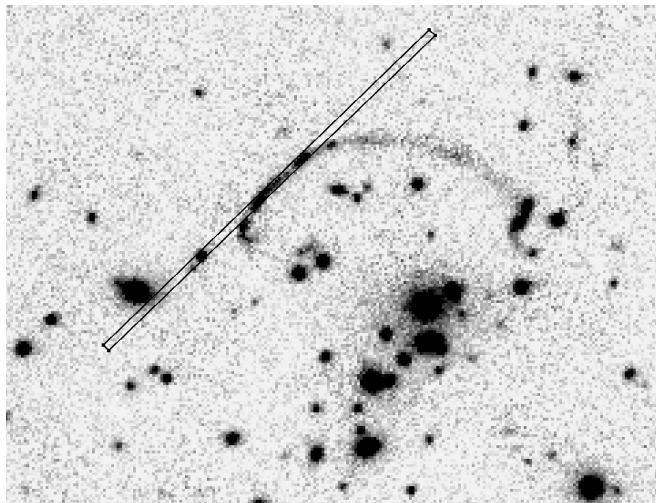


Figure 1. Finderchart for RCS0327. This J-band image from Wuyts et al. (2010) illustrates how we positioned the NIRSPEC slit, which is $42 \times 0.76''$. N is up and E is left. For simplicity we show the slit centered on the source; in fact it the source was placed on the left half and then the right half of the slit (“an AB pattern”), with the nods separated by 10–15″.

For each filter, we combined the individual flux-calibrated 1D spectra with a weighted average, producing one fluxed spectrum for each of the three filters.

We fit line fluxes as follows. We fit each isolated line with a Gaussian to measure the line flux, using Levenberg–Marquardt fitting. The continuum used was the mean flux in an adjacent spectral region, chosen by hand for each line. For partially-overlapping lines, we simultaneously fit multiple Gaussians using A. Marble’s implementation of the IDL Levenberg-Marquardt least-squares fitting code MPFITFUN (Markwardt 2009). We

Table 2
Measured line fluxes for RCS0327

line	λ_{obs}	flux	dflux
Filter N1			
[O II] 3727	1.00808	72.0	0.2
[Ne III] 3869	1.046273	7.8	1.3
H8+HeI 3890	1.05195	6.6	0.4
H ϵ	1.0729	<3.8	limit
H δ	1.1093	7.1	1.7
Filter N3			
H γ	1.17385	13.5	2
[O III] 4363	1.1800	<1.5	limit
[Ar IV] 4741	1.2825	<3.0	limit
H β	1.31473	32.4	1.1
[O III] 4959	1.34111	49.3	1.6
[O III] 5007	1.35409	159	1.4
Filter N6			
[N II] 6548	1.77115	3.85	0.8
H α	1.77488	116	1.2
[N II] 6583	1.78002	7.4	1.2
[S II] 6716	1.81663	6.7	0.3
[Ar III] 7136	1.9296	2.8	0.3

Note. — Measured line fluxes. Columns are line ID, observed wavelength, lineflux in units of $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, and uncertainty in the lineflux.

report line fluxes in Table 2.

We assume a cosmology of $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Solar abundances are taken from Table 1 of Asplund et al. (2009). The initial mass function (IMF) is Chabrier (2003) unless noted.

3. RESULTS

Figure 2 plots the spectra. Several of the nebular emission lines are detected at very high signal-to-noise ratio (SNR); for example, we detect $\sim 50,000$ net counts in the H β line. Continuum is detected in filters NIRSPEC-1 and NIRSPEC-3 at $\text{SNR} \lesssim 1$ per pixel. Continuum is not confidently detected near the lines of interest in NIRSPEC-6, which is unsurprising given the low atmospheric transmission at those wavelengths.

3.1. Extinction

Based on SED fitting, Wuyts et al. (2010) report low extinction values of $E(B-V) = 0.03$ to 0.11, depending on metallicity and spatial position. Given the potential degeneracies when fitting SEDs between extinction and age and star formation rate, a spectroscopic measurement of the extinction is desired.

The α , β , γ , and δ transitions of the Balmer series are detected; H ϵ is formally undetected. The correction for stellar absorption, $\sim 2\text{\AA}$ (McCall et al. 1985), is negligible at these extremely high equivalent widths: $E_r = 430 \pm 70 \text{\AA}$ and $100 \pm 20 \text{\AA}$ for H β and H γ .

H α appears in filter NIRSPEC-6; H γ and H β in NIRSPEC-3; and H δ and H ϵ in NIRSPEC-1. A line is detected at the position of H8, but is too strong to be H8 alone. We suspect it is a blend of H8 with two He I lines, as in seen in the Orion Nebula (Osterbrock et al. 1992).

Because they appear in the same filter, the H β /H γ and H δ /H ϵ line ratios are free from relative fluxing errors. We measure $\text{H}\beta/\text{H}\gamma = 2.39 \pm 0.37$, which for Case B recombination at $T = 10^4 \text{ K}$ and $n_e = 100 \text{ cm}^{-3}$ yields

$E(B-V) = 0.23 \pm 0.23^6$ The $H\delta/H\epsilon$ ratio of > 1.87 does not constrain the extinction given measurement errors. The best spectroscopic measure of extinction therefore comes from the $H\beta/H\gamma$ ratio, which for $R=3.1$, yields $A_v = 0.7 \pm 0.7$.

The high end of this range is inconsistent with the blue color of the arc, as quantified by the SED fitting of Wuyts et al. (2010). Therefore, in the rest of the paper we will report results assuming first $A_v = 0.0$ and then $A_v = 0.7$. This considerable uncertainty in the extinction will limit how well we can measure spectral diagnostics that span a large range of wavelength, for example R_{23} . A more precise measurement of the extinction awaits simultaneous observations of $H\alpha$ and $H\beta$, or a longer integration on $H\gamma$ and $H\beta$.

3.2. Tweaking the flux calibration

As discussed in §2, there may be fluxing offsets among the three filters. We address this issue using the Balmer series. Assuming an extinction of $A_v = 0.7$ as measured from the $H\beta/H\gamma$ ratio in NIRSPEC-3, we tweak the relative scalings of the NIRSPEC-1 and NIRSPEC-6 spectra to bring $H\alpha/H\beta$ and $H\delta/H\beta$ to the appropriate ratios for this extinction. This increases the flux in NIRSPEC-1 by a factor of 1.15 relative to NIRSPEC-3, and decreases the flux in NIRSPEC-6 by a factor of 0.61 relative to NIRSPEC-3. These are reasonable corrections given the slit loss variation expected from seeing changes and atmospheric transparency issues in NIRSPEC-6. Fluxes reported in this paper reflect this scaling.

In Table 2 we report the line fluxes in filters NIRSPEC-1, -3, and -6. Line flux ratios within a filter should be precise, limited by the uncertainty in line-fitting. When calculating a line flux ratio for lines spanning different filters, one should include a 10% relative fluxing uncertainty.

3.3. Fraction of the galaxy covered

To estimate the fraction of the galaxy covered by the slit, we use the PANIC/Magellan images in J and K_s of Wuyts et al. (2010), which had seeing of $\text{FWHM}=0.57''$ and $0.51''$. We estimate that $37 \pm 5\%$ of the total arc light falls into a slit positioned as in Figure 1, neglecting slit losses. We compute slit losses for seeing of $0.8\text{--}0.9''$ and pointing errors of $0\text{--}0.25''$. We conclude that $32\% \pm 4\%$ (random) $\pm 1\%$ (systematic) of the continuum light should have been captured by our NIRSPEC slit.

We now estimate this quantity in an alternate way. We measure the continuum adjacent to the 3737 \AA and $H\beta$ lines as 6.1×10^{-18} and $6.0 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ (using a robust average), with measurement errors of 10–20%. These continua levels are 21% of the continuum intensity in the spectral energy distribution in Figure 7 of Wuyts et al. (2010), which is the best fit to the u, B, g, r, i, z, J, H, K_s photometry of the whole arc.

These two methods disagree by 38%. We suspect that the continuum method is as fault, as the continuum is not well detected, and small DC offsets might plausibly be introduced in sky subtraction. (Indeed, this uncertainty in the continuum level is why we chose to flux using AOV stars rather than multiplying line equivalent widths by

f_λ from broadband photometry as in Teplitz et al. 2000.) Therefore, we adopt the first method, and will multiply our NIRSPEC fluxes by the reciprocal, 3.12 ± 0.4 , to convert to the expected line flux over the whole arc.

3.4. Average Magnification

Wuyts et al. (2010) measure an average magnification of $u = 17.2 \pm 1.4$ for RCS0327. Our current lensing model, based on ground-based photometry (Wuyts et al. 2010), has insufficient spatial resolution to determine the magnification of each small knot. Thus, at present we cannot quote a reliable magnification for the portion of the arc that falls in our NIRSPEC slit. It is likely that some of the bright knots are much more highly magnified than the arc on average. For the time being we will adopt the average magnification, with these caveats. Fortunately, except for the star formation rate derived from the Balmer lines, none of the results in this paper depend on the magnification within the NIRSPEC slit.

3.5. Redshift

We fit the mean emission line redshift as 1.7037 ± 0.0001 using the NIST linelist,⁷ excluding [O II] 3727 because it is a partially resolved doublet. This compares perfectly with the redshift of rest-UV emission lines in our (not yet published) MagE/Magellan spectrum: 1.70369 ± 0.00006 . The MagE spectrum also yields a redshift for absorption lines in the interstellar medium: Si II 1260, Si II 1808, and Al II 1670, recommended to us by C. Tremonti as isolated ISM lines, yield an ISM redshift of 1.702671 ± 0.0003 . Thus, the MagE spectra show that the interstellar medium is blueshifted from the nebular lines by $110 \pm 30 \text{ km s}^{-1}$. Our measured redshifts are 3 and 2σ higher than the 1.7009 ± 0.0008 reported by Wuyts et al. (2010) using a combination of the [O II] 3727 and C III] 1909 emission lines and the Fe II and Mg II absorption lines.

3.6. Velocity width

We extract arc lamp spectra using the same apertures as the science frames, and combine with the same weighted average technique as for the science frames. For each filter, we fit the instrumental linewidth versus wavelength relation with a linear fit, then interpolate the instrumental linewidth at the wavelength of each astronomical line of interest. For example, at the observed wavelength of $H\alpha$, the arc lines have $\text{FWHM}=13.6 \text{ \AA}$ compared to $\text{FWHM}=15.3 \text{ \AA}$ observed for $H\alpha$; from this we infer $\sigma = 50 \pm 2 \text{ km s}^{-1}$. For $H\gamma$, $H\beta$, $\lambda 4959$, and $\lambda 5007$, we measure $\sigma = 76, 59, 49, 23 \text{ km s}^{-1}$. With $H\alpha$, this gives an average nebular line velocity dispersion of $\sigma = 51 \text{ km s}^{-1}$ with an error in the mean of 9 km s^{-1} .

We fit the [O II] 3726, 3729 doublet with two Gaussians, fixing the line centers using the NIST vacuum wavelengths and redshift from §3.5, and forcing the two linewidths to be the same, while varying the continuum, line amplitudes, and the linewidth. This fitting finds that $\sigma = 51 \pm 1 \text{ km s}^{-1}$ for [O II].

Because the lensing morphology of RCS0327 is complex, we cannot yet compute a meaningful effective radius, as needed to determine a dynamical mass from the

⁶ Using the extinction law of Cardelli et al. (1989).

⁷ <http://www.pa.uky.edu/~peter/atomic/>

velocity width. Upcoming HST observations should clarify this matter.

3.7. Star formation rate

Wuyts et al. (2010) estimated the SFR by fitting the broad-band optical and near-IR photometry, finding a SFR constraint of $< 77 M_{\odot} \text{ yr}^{-1}$ for 40% solar metallicity. (For solar metallicity the SFR is lower).

We also estimate the star formation rate from mid-IR photometry. We measure the main arc and counter-image separately, finding MIPS/Spitzer $24 \mu\text{m}$ flux densities of $1040 \pm 153 \mu\text{Jy}$ and $43 \pm 11 \mu\text{Jy}$ respectively. Scaling by the average magnifications for the main arc and counter-image from the current lensing model (Wuyts et al. 2010) yields de-lensed $24 \mu\text{m}$ flux densities of $60 \pm 10 \mu\text{Jy}$ for the main arc versus $21 \pm 6 \mu\text{Jy}$ for the counter-image. The de-lensed $24 \mu\text{m}$ flux density of the main arc corresponds to a star formation rate of $106 \pm 30 M_{\odot} \text{ yr}^{-1}$ using the prescription of Rieke et al. (2009). The equivalent value from the counter-arc is $18 \pm 8 M_{\odot} \text{ yr}^{-1}$.

The significant difference between the de-lensed flux densities suggests that the source is strongly non-uniform; resolving this requires a more precise lensing model and a robust comparison of the observed image-plane data (both spectra and photometry) in the source plane. Until HST imaging of this source is available, the best comparison to the spectra presented here is the main arc, as the spectra sample a portion of that image.

Thirdly, we estimate the star formation rate from the NIRSPEC spectra, using the $\text{H}\beta$ line flux within the aperture, assuming the extinction from $\text{H}\beta/\text{H}\gamma$, and the $\text{SFR}(\text{H}\alpha)$ conversion of Kennicutt (1998), modified for a Chabrier (2003) IMF following Eqn. 10 of Rieke et al. (2009):

$$L(\text{H}\alpha) = f(\text{H}\beta)(\text{H}\alpha/\text{H}\beta)4\pi d_L^2/u \quad (1)$$

$$= (3.2 \pm 0.1) \times 10^{-15} (3.6 \pm 0.8) 4\pi d_L^2/u \quad (2)$$

$$= (2.25 \pm 0.5) \times 10^{44}/u \quad (3)$$

$$= (5.9 \pm 1.3) \times 10^{10}/u L_{\odot} \quad (4)$$

$$\text{SFR}(\text{H}\alpha) = 0.66 \times 7.9 \times 10^{-42} \text{ erg s}^{-1} \quad (5)$$

$$= (1170 \pm 270 M_{\odot} \text{ yr}^{-1})/u \quad (6)$$

A rough method of computing the total star formation rate is to divide by the average magnification from Wuyts et al. (2010) and multiply by the fraction of the light in the image plane captured by the NIRSPEC slit (from §3.3). This yields $\text{SFR} = 210 \pm 60 M_{\odot} \text{ yr}^{-1}$, which is extremely high.

The star formation rate derived from the Balmer lines is considerably higher than inferred from the broadband photometry or the $24 \mu\text{m}$ flux. The cause is not measurement error nor fluxing error. (We have cross-checked the fluxing in multiple ways.) The Balmer lines are simply incredibly bright in these knots of RCS0327, with $\text{H}\beta$ for example eight times brighter than in cB58.

By spectroscopically targeting the brightest knots in RCS0327, we may well be biased toward the regions with highest surface brightness and/or highest magnification.

The current lensing map (Wuyts et al. 2010) lacks the high spatial resolution required to determine the magnification of each knot. However, it does suggest that the magnification of this part of the arc is significantly higher than other parts of the arc. Thus, the rough method of computing the total SFR is probably wrong because it uses the average magnification of the whole arc, rather than the magnification of each pixel within the NIRSPEC slit.

A simpler method would be to measure the emission line flux over the entire arc, or at least all of the counter-arc, which is more compact and thus easier to map. Pending narrow-band HST imaging of $\text{H}\beta$ should provide this coverage for RCS0327.

The three different methods give quite different answers for the star formation rate. Only the brightest portion of the main arc was observed with Nirspec; this portion of the arc is possibly the brightest because of a conflation of a bright region within the source with a region of larger-than-average magnification, from which we would expect the spectral star formation rate to be larger than that derived from the average main arc $24 \mu\text{m}$ flux density, as observed. A robust treatment of this comparison awaits a refined lensing model and reconstruction of source in the source plane.

Imaging is also biased toward regions of high surface brightness, and over-represents certain portions of the galaxy, but it does capture the entire image plane, and thus should deliver accurate quantities like average magnification, total magnitudes, and colors.

3.8. Ionization parameter

Figure 1 of Kewley & Dopita (2002) illustrates the $\lambda 5007/\lambda 3727$ flux ratio as a diagnostic of the ionization parameter. For an O abundance of 20–40% solar (on the Asplund system), eqn. 12 of Kewley & Dopita (2002)⁸ yields an ionization parameter of $\log U = -2.73$ to -2.85 for $A_v = 0.7$. For $A_v = 0$, $\log U$ is higher by 0.1 dex. The uncertainty due to extinction dominates over the flux uncertainty.

3.9. Electron Density

The two-component fit to the $[\text{O II}]$ doublet in §3.6 found a line flux ratio of $f(3726/3729) = 0.893 \pm 0.024$, where this uncertainty is dominated by the uncertainty in deblending the doublet. This ratio is density-dependent (c.f. Figure 5.8 of Osterbrock & Ferland 2006.) Using `stdas.analysis.temden` in IRAF,⁹ our measurement corresponds to a tight measurement of the density: $n_e = 235_{-26}^{+28}$ at $T_e = 10^4 \text{ K}$, and $n_e = 252_{-28}^{+30} \text{ cm}^{-3}$ at $1.2 \times 10^4 \text{ K}$.

The ratio of the C III 1907/1909 doublet also constrains the density (Rubin et al. 2004, their Figure 2.) Fitting the doublet in our Mage/Magellan spectra (Rigby et al. in prep.) in the same way as the 3727 doublet, we measure a flux ratio of $f(1907/1909) = 2.16 \pm 0.3$. This ratio is unphysical by 1.7σ , as the zero-density limit is

⁸ Which uses the Anders & Grevesse (1989) abundances; we convert to Asplund et al. (2009).

⁹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

1.65 for pure C13, and 1.51 for pure C12 (Rubin et al. 2004). While deeper data should provide a better measurement of this line ratio, the current measurement of the C III] ratio is consistent with the low density regime of this diagnostic of $n_e \lesssim 10^{3.5} \text{ cm}^{-3}$.

The doublet ratio of [S II] 6716, 6731 Å also constrains the electron density (c.f. Fig. 5.8 of Osterbrock & Ferland 2006.) Unfortunately, the redder line is mostly lost to a skyline. Fitting in the same way as for the 3727 doublet, we measure a doublet ratio of 2.4 ± 0.4 , which is unphysical by 2.4σ (the zero density limit is 1.43). This unphysical result is likely due to the skyline contamination; we conclude that in this case we cannot use the [S II] ratio to constrain the electron density.

To summarize, the [O II] 3727 doublet ratio provides a tight density constraint, which is consistent with the low density regime indicated by the C III] 1909 doublet. The [S II] doublet is contaminated by a skyline and provides no density constraint.

3.10. Electron Temperature

The ratio [O III] ($\lambda 5007 + \lambda 4959$)/ $\lambda 4363$ constrains the electron temperature with almost no n_e dependence (c.f. Izotov et al. 2006; Figure 5.1 of Osterbrock & Ferland 2006). The ratio in RCS0327 is > 139 for $A_v = 0.0$, and > 121 for $A_v = 0.7$. Following Izotov et al. (2006), this corresponds to $T_e \leq 1.14 \times 10^4 \text{ K}$, $\leq 1.20 \times 10^4 \text{ K}$, and $\leq 1.26 \times 10^4 \text{ K}$ for $A_v = 0.0, 0.7$, and 1.4 .

3.11. Oxygen abundance

We constrain the oxygen abundance via the “direct” or “ T_e ” method following Izotov et al. (2006), using the non-detection of [O III] 4363 Å to constrain T_e , [O II] 3727 Å and $H\beta$ to constrain (O^+/H^+) and [O III] 4959, 5007, and $H\beta$ to constrain (O^{2+}/H^{2+}) . Since He II 4686 is not detected, we can ignore the contribution of O^{3+} . The result is $12 + \log(O/H) > 8.21$ for $A_v = 0.0$ and > 8.14 for $A_v = 0.7$; these are 0.48 and 0.55 dex lower than the solar value of 8.69 ± 0.05 (Asplund et al. 2009).

We compare this “direct” lower limit on the oxygen abundance to results from the bright line diagnostics. We follow the calibrations for each diagnostic, then remove the relative offsets via the conversions of Kewley & Ellison (2008), so that all diagnostics are on the system of the N2 index of Pettini & Pagel (2004). The bright line results are as follows:

- The N2 index, $\log([NII]/H\alpha) = -1.19 \pm 0.07$, yields $12 + \log(O/H) = 8.20 \pm 0.04$ by the third-order polynomial calibration of Pettini & Pagel (2004), and 8.22 ± 0.04 by their linear fit. Each of these two calibrations was reported to have a 1σ spread against T_e of 0.18 dex (Pettini & Pagel 2004). Reddening is irrelevant.
- The N2 index calibration of Denicoló et al. (2002) yields $12 + \log(O/H) = 8.20 \pm 0.05$.
- The O3N2 index, $\log[(5007/H\beta)/(NII/H\alpha)] = 1.88 \pm 0.07$, yields $12 + \log(O/H) = 8.16 \pm 0.02$ by the calibration of Pettini & Pagel (2004), which

has a 1σ spread of 0.14 dex. Reddening is irrelevant.

- The index $\log[NII6584]/[OII3727]$ is -0.99 ± 0.07 for $A_v = 0$ and -1.19 ± 0.07 for $A_v = 0.7$. The calibration of Kewley & Dopita (2002) as modified by Kewley & Ellison (2008) produces a double-valued abundance: $12 + \log(O/H) = 8.21, 8.34 \pm 0.06$ for $A_v = 0$; and $12 + \log(O/H) = 8.21, 8.22 \pm 0.06$ for $A_v = 0.7$.
- The Ne3O2 index, $\log([NeIII]\lambda 3869/[OII]\lambda 3727) = -0.96 \pm 0.07$, yields $12 + \log(O/H) = 8.19 \pm 0.08$ via the calibration of Shi et al. (2007). Reddening is irrelevant. This diagnostic does not appear in Kewley & Ellison (2008), so we cannot remove any calibration offsets.

The R_{23} index, $\log[(\lambda 3727 + \lambda 4959 + \lambda 5007)/H\beta]$, is unfortunately double-valued as well. We measure $\log R_{23}$ as 0.94, 0.96, 0.99 for $A_v = 0.0, 0.7, 1.4$, all with uncertainties of ± 0.02 from the propagated flux uncertainty. (This is similar to the value of 0.92 measured for cB58 by Teplitz et al. 2000.) Such a high R_{23} requires a high ionization parameter ($\log U \geq -2.87$ from Fig. 5 of Kewley & Dopita 2002). The several R_{23} calibrations methods use various means to separate the “lower branch” and “upper branch”, typically $[N II]/[O II]$ or $[N II]/H\alpha$ (Kewley & Ellison 2008). Unfortunately, for RCS0327 these ratios are on the border between upper and lower branch. Thus, we compute the abundance for each branch:

- Zaritsky et al. (1994) published an R_{23} calibration for the upper branch only. We use it with caution since RCS0327 is not clearly in either the upper or lower branch. For $A_v = 0$, this calibration yields $12 + \log(O/H) = 8.15 \pm 0.02$. For $A_v = 0.7$, it yields 8.14 ± 0.02 .
- The Pilyugin & Thuan (2005) method yields $12 + \log(O/H) = 8.26 \pm 0.05$ and 8.07 ± 0.08 for the upper and lower branches for $A_v = 0$, and 8.19 and 8.22 (same uncertainties) for $A_v = 0.7$.
- The Kobulnicky & Kewley (2004) method yields $12 + \log(O/H) = 8.19$ and 8.16 ± 0.02 for the upper and lower branches and $A_v = 0$, and 8.17 ± 0.02 for both branches at $A_v = 0.7$.

These inferred abundances are plotted in Figure 5.

3.12. Abundances of other elements

Following Izotov et al. (2006), we constrain the abundance of N^+ , Ne^{2+} , Ar^{2+} , and Ar^{3+} relative to H^+ . Unlike O, the full suite of ionization states is not observed for these elements, so we must apply ionization correction factors to infer abundances.

- **N:** We derive $12 + \log(N/H) > 6.53$ (> 6.42) for $A_v = 0.0$ (0.7). Thus, N is depleted relative to the solar value by no more than 1.41 dex. The uncertainty from extinction is larger than from flux uncertainties.

- **Ne:** We derive $12 + \log(Ne/H) > 7.33 \pm 0.09$, which is 0.60 dex below solar.
- **Ar:** We derive $12 + \log(Ar/H) > 5.54 \pm 0.18$, which is 0.86 dex below solar.

Though we have measured lower limits on all abundances, we can tightly constrain the key abundance ratios, which depend only weakly on T_e :

- **N/O:** For the maximum allowed T_e , $\log(N/O) = -1.70 \pm 0.02$. If the $\lambda 4363$ flux is one-third the upper limit, then T_e is 70% of the maximum, and $\log(N/O) = -1.89 \pm 0.04$. These ratios are 0.84 ± 0.02 to 1.03 ± 0.04 dex below the solar abundance ratio.
- **Ne/O:** For the maximum allowed T_e , $\log(Ne/O) = -0.89 \pm 0.09$ for $A_v = 0$, which is 0.13 dex below the solar ratio. For $A_v = 0.7$ the ratio is $\log(Ne/O) = -0.72 \pm 0.09$, which is 0.04 dex above solar. At 70% of the maximum permitted T_e , the constraints are from 0.03 dex below to 0.14 dex above solar. Thus, no matter the actual T_e , the Ne/O ratio must be solar-like.
- **Ar/O:** For the maximum allowed T_e , $\log(Ar/O) = -0.89 \pm 0.18$, which is 0.13 dex below the solar value. For 70% of the maximum permitted T_e , $\log(Ar/O) = -0.62 \pm 0.18$, which is 0.14 dex above solar.

Thus, RCS0327 has an abundance pattern in which the O abundance is at least 29% of solar, the Ne/O and Ar/O ratios are solar-like, and the N/O ratio is less than 15% of the solar ratio.

3.13. Joint constraints on physical conditions from photoionization models

As a cross-check on these diagnostics, we run spectral synthesis and photoionization models. The UV spectra come from Starburst 99 (v5.1, web version; Leitherer et al. 1999 and Vázquez & Leitherer 2005), assuming continuous star formation, an upper mass cutoff of $100 M_\odot$, the default IMF parameters, the Padova AGB models, and with stellar metallicity set at 40% of solar. We feed these UV spectra to the photoionization code Cloudy version c08.00 (Ferland et al. 1998), running a grid of models of given electron density and starburst age, and in each model optimizing the metallicity and ionization parameter, as constrained by the measured line intensities relative to $H\beta$, assuming a foreground screen extinction of $A_v = 0.7$, the measured uncertainties for lines contiguous with $H\beta$, and 20% relative fluxing errors for noncontiguous lines. The abundance pattern is “H II” region. Our grid of electron density covers $\pm 1\sigma$ of the value measured in §3.9.

Cloudy computes an average electron temperature of $T_e = 1.19$ to 1.24×10^4 K, which is consistent with the value inferred in §3.10. Cloudy converges on an oxygen abundance in the range $12 + \log(O/H) = 8.07$ to 8.13 , and an ionization parameter in the range $\log U = -2.57$ to -2.42 . Figure 4 illustrates these constraints. Thus, Cloudy converges on an O abundance that is 0.1 dex lower than via the T_e method, and a $\log U$ that is higher

by 0.2–0.3 dex than derived from the Kewley & Dopita (2002) method.

The source of this discrepancy may lie with different assumptions of abundance pattern, filling factor, atomic data, or ionizing stellar spectra compared to Kewley & Dopita (2002). Resolving this moderate discrepancy is outside the scope of this paper at this time, but it provides a caution that one must be careful, when comparing derived physical properties of galaxies, to use the same methodology. In this paper, we will adopt the $\log U$ derived via the Kewley & Dopita (2002) method, so that we may compare to other lensed galaxies in the literature.

Dust grains were not included in the Cloudy models. As a test, we added dust grains with the same metallicity and abundance pattern as the gas, which changed the inferred metallicity and ionization parameter by only 2% and 1%.

4. DISCUSSION

Since this is the first investigation of the rest-frame optical lines in RCS0327, only the brightest “knots” were targeted, representing only $32\% \pm 4\%$ (random) $\pm 1\%$ (systematic) of the total light of the arc (§3.3). RCS0327 was selected as the brightest and one of the largest lensed sources in a large survey; despite its exceptional appearance, SED and lensing modeling show it to be a fairly typical object (Wuyts et al. 2010). As such, it is likely that the high surface brightness portions of the source galaxy coincide with high magnification, and that this coincidence makes RCS0327 such a spectacular example of strong lensing. This supposition would explain the differing star formation rates derived from $24\mu\text{m}$ imaging of the main arc and counter-image, as noted in §3.7. Moreover, because the lensed source straddles the lensing tangential caustic (c.f. Figure 6 in Wuyts et al. 2010), the lens model suggests that only some regions of the galaxy are represented in the giant arc, namely the core, and one of two apparent spiral arms, and may be highly magnified. Thus the giant arc is likely not a fair representation of the source galaxy as a whole.

Since superb spectra can be quickly obtained for these bright knots, it is their physical conditions that we probe in this paper, with a caveat that these may not be “ordinary” regions of this galaxy. Once the arc has been fully mapped in these emission lines, and a high-resolution lensing map has been derived from HST imaging, we should understand how much the physical conditions vary across the source plane, and locate the brightest knots in the source plane. It will then be possible to fully contextualize our results in terms of the range of physical conditions across the spatial extent of RCS0327.

For now, we assume that the knots for which we have spectra are representative. Since these are highest-quality rest-frame optical spectra ever obtained for a $z=2$ galaxy, and yield precise measurements of the physical conditions, we now consider these measurements in the context of the literature, and the conditions under which stars form in the distant universe.

4.1. Extinction

The following E(B-V) extinctions have been measured from Balmer decrements in lensed blue galaxies: 0.27 for cB58 (Teplitz et al. 2000); 0.28 ± 0.04 for the

Clone (Hainline et al. 2009); 0.45 ± 0.04 for the Cosmic Horseshoe (Hainline et al. 2009); 0.59 ± 0.08 for J0900 (Bian et al. 2010); 0.67 ± 0.21 for the 8 o'clock arc (Finkelstein et al. 2009). Our measurement of $E(B-V) = 0.23 \pm 0.23$ for RCS0327 is consistent with the lower part of this range, but the uncertainty is large, stemming mostly from the flux uncertainty in $H\gamma$. A spectrograph that obtains $H\alpha$ and $H\beta$ simultaneously, for example FIRE on Magellan or LUCIFER on LBT, would provide a very precise measurement of the Balmer decrement in this galaxy, allowing a detailed comparison of the relative extinctions suffered by the gas and the stars.

4.2. The reliability of O abundance diagnostics at $z=2$

For RCS0327, the non-detection of [O III] 4363 Å sets a strict constraint on the oxygen abundance via the “direct” T_e method: it must be no more than 0.55 dex (0.48 dex) below the solar value for $A_v = 0.7$ ($A_v = 0$), or 28% and 33% as percentages of solar. Neon provides a cross-check on this abundance measurement. Since both Ne and O are alpha-group elements, their ratio should be solar-like, and indeed our measured ratio is solar with an uncertainty of ± 0.14 dex. We believe this to be the first time the Ne/O ratio has been measured at $z \sim 2$.

We now accept the T_e -method’s oxygen abundance measurement, and assess the reliability of the “bright line” diagnostics.

These diagnostics are empirically calibrated at $z=0$ against the T_e method, or calibrated with photoionization models. As such, they implicitly assume densities and ionization parameters typical of nearby galaxies, which may not be appropriate for high-redshift galaxies, for reasons of luminosity bias and evolution in the galaxy population. In addition, these diagnostics have significant relative offsets (up to 0.7 dex) at $z=0$ whose origins are not understood and which must be empirically calibrated away using SDSS galaxies (Kewley & Ellison 2008); it is not clear that for rapidly star-forming $z=2$ galaxies these offsets will be the same.

Thus, it is important to test these bright-line diagnostics *in situ* at $z=2$. Figure 5 compares the O abundances inferred in §3.11 for the bright-line diagnostics in RCS0327. For ease of comparison, we plot $A_v=0$ and $A_v=0.7$ separately. We divide the calibrations into five categories: [N II]/[O II], Ne3O2, N2, O3N2, and R23 methods.

The [N II]/[O II] diagnostic (Kewley & Dopita 2002) is consistent with the T_e method, in part because its double-valued results and the large uncertainty covers 0.3 dex of parameter space. Because this index has a large extinction correction, we cannot adequately test it until the extinction of RCS0327 is more precisely measured.

The Ne3O2 diagnostic is consistent with the T_e method, especially for $A_v > 0$.

The N2 calibrations of Pettini & Pagel (2004) and Denicoló et al. (2002) are consistent with the lower limit from the T_e method, especially for $A_v > 0$. This test is especially important, since this diagnostic is the one used to measure the evolution in the mass-metallicity relation from $z=0$ to $z=2$ (Erb et al. 2006) and $z=3$ (Mannucci et al. 2009; Maiolino et al. 2008).

The O3N2 diagnostic (Pettini & Pagel 2004) yields an abundance that is 2.5σ below the T_e lower limit for $A_v = 0$, and is thus inconsistent with the T_e limit. How-

ever, moderate extinction ($A_v = 0.7$) makes the results consistent. The O3N2 result is lower than the abundances from the N2 and [N II]/[O II] indices.

The R23 index has a large extinction correction. As such, it is difficult to assess the performance of this diagnostic given the current uncertainty in the extinction of RCS0327. For $A_v = 0$ only the upper branch of Pilyugin & Thuan (2005) is consistent with the T_e result; for $A_v = 0.7$ the Pilyugin & Thuan (2005) method is also consistent. The Zaritsky et al. (1994) method produces an inconsistent result, but this is unsurprising since it is only valid for high metallicity.

This is the first test *in situ* at $z=2$ of the bright line abundance diagnostics for a star-forming galaxy of typical metallicity. To summarize, the R23 and [N II]/[O II] methods are not inconsistent with the T_e method so long as the extinction exceeds zero; the definitive test must await a more precise extinction measurement, since both diagnostics have large reddening corrections. The Ne3O2 diagnostic is consistent with the T_e method, though the errorbars are larger than for N2 and O3N2, since [Ne III] is not a terribly bright line. The N2 and O3N2 methods are most constraining given the current extinction measurement; of these, the N2 results are entirely consistent with the T_e method, and the O3N2 diagnostic is consistent only given significant but plausible extinction.

The only other published T_e detection at $z=2$ of which we are aware is in Lens22.3, a low-mass, low-metallicity galaxy behind Abell 1689 (Yuan & Kewley 2009). For Lens22.3, the T_e method yields $12 + \log(O/H) = 7.5 \pm 0.1$ for zero extinction and 7.3 ± 0.1 for high extinction. We apply the Pettini & Pagel (2004) N2 and O3N2 calibrations to the published line fluxes of Yuan & Kewley (2009) (N II is not detected). From $N2 < -2.30$ comes an abundance of $12 + \log(O/H) < 7.47$ (7.59) using the third-order (linear) N2 calibration. The O3N2 index, $\log O3N2 > 3.11$, yields $12 + \log(O/H) < 7.73$ on the original Pettini & Pagel (2004) scale, which is outside the range that can be converted to the N2 frame (Kewley & Ellison 2008). These N2 and O3N2 measurements are consistent with the T_e result. However, all these diagnostics are highly inconsistent with the R23 result of $12 + \log(O/H) = 8.0-8.3$ (Yuan & Kewley 2009).

Yuan & Kewley (2009) noted the discrepancy between the R23 and T_e results, and attributed the fault to the T_e method. Given the consistency between the N2, O3N2, and T_e methods, we suggest that it may instead be R23 that is failing in Lens22.3.

4.3. The reliability of O abundance diagnostics in other $z=2$ lensed galaxies

Only in RCS0327 and Lens22.3 are the spectra sufficient to measure abundances via the T_e method. However, the bright line diagnostics have been used for a number of galaxies. A re-analysis of the mass-metallicity relation at $z \geq 2$ is outside the scope of this paper. However, it is appropriate at this juncture to re-examine the N2 and O3N2 diagnostics in light of the results above. In Figure 6 we plot the mass-metallicity relation at $z=2$, using literature results for lensed and unlensed galaxies, and our results for RCS0327. For fair comparison, we convert stellar masses to the Chabrier (2003) IMF, take line fluxes from the literature and apply the N2 and

O3N2 calibrations of Pettini & Pagel (2004), brought to the N2 system via the conversion¹⁰ of Kewley & Ellison (2008).

We plot four lensed galaxies in Figure 6: cB58 (Teplitz et al. 2000), J0900+2234 (Bian et al. 2010), the 8 o'clock arc (Finkelstein et al. 2009), and RCS0327 (this work). These four galaxies span a range of 400 in stellar mass, extending below the mass range probed by stacked samples (Erb et al. 2006). In all four cases, the O3N2-derived abundances are systematically lower than those derived from N2, strikingly so in the case of the 8 o'clock arc. (Recall that the relative offset between these indices, as measured in SDSS at $z=0$, has already been removed.) These offsets were noted for each galaxy in their respective papers, but were dismissed as less than the calibration dispersion of the diagnostics. The Clone and Horseshoe lack stellar mass measurements to plot them on Figure 6, but comparison of their N2 and O3N2-derived abundances shows the same trend: the O3N2 index is low by 0.16 and 0.07 dex.

It is clear from a consideration of all six lensed galaxies that the O3N2 and N2 indices are systematically offset at $z=2$. While this offset is small for the galaxies of intermediate metallicity, it is large for the 8 o'clock arc at the high metallicity end.

This behavior is not surprising when we consider that O3N2 has $5007/H\beta$ in the numerator, and that what makes $z=2$ galaxies stand out in the BPT diagram Baldwin et al. (1981) is their high $5007/H\beta$ compared to SDSS galaxies. Thus, we suggest that high ionization conditions in $z=2$ galaxies cause the O3N2 diagnostic to function poorly at these redshifts.

4.4. Lensed galaxies and the $z=2$ mass-metallicity relation

RCS0327 has a stellar mass of $\log(M_*) = 10.0 \pm 0.1 M_\odot$ (Wuyts et al. 2010); both the main arc and the counter-arc give consistent results. This is 0.94 ± 0.14 dex lower than the Schechter function parameter M_{star}^* at $z=2.0$ (Marchesini et al. 2009), and lower than most of the Lyman break galaxies in Erb et al. (2006). The low measured velocity dispersion qualitatively supports a low mass. In the mass-metallicity plane, RCS0327 lies significantly, 0.17 ± 0.04 dex, below the $z=2$ relation of Erb et al. (2006). This offset is too large to be measurement error, and so we attribute it instead to a real abundance difference: RCS0327 is metal-poor by about 50% for its stellar mass and redshift, compared to Erb et al. (2006).

J0900+2234 shows this effect to an even greater degree (Bian et al. 2010), since it has almost the same N2-derived oxygen abundance and a slightly higher stellar mass.

On the high-mass end, the N2-derived oxygen abundance of the 8 o'clock arc is quite consistent with the high-mass side of Erb et al. (2006), perhaps 0.05–0.08 dex low. By contrast, at the very low-mass end, cB8 lies far off the relation, having a very low stellar mass but a high oxygen abundance, more typical of the mass-metallicity relation at $z=0$ than at $z=2-3$. Thus, even from a modest sample of four lensed galaxies, we are

already beginning to probe the intrinsic spread in the mass-metallicity relation at $z=2$.

4.5. Abundance pattern

In §3.12 we constrained the N/O ratio as $\log(N/O) \leq -1.70$. For plausible values of T_e the ratio can be lower by 0.2 dex. These abundances are startlingly close to the values measured for cB58: $\log(N/O) = -1.76 \pm 0.2$ dex (Pettini et al. 2002) and $12 + \log(O/H) = 8.26$ (Teplitz et al. 2000).¹¹ Even though RCS0327's stellar mass is 18 times larger than cB58's, and its redshift lower, star formation in these two galaxies has produced very similar ratios of N, O, and H. UV spectroscopy for RCS0327, as in Pettini et al. (2002) for cB58, should allow element-by-element comparison of abundance ratios.

For now, we concentrate on the N/O ratio. RCS0327 lies near the intersection of the primary and secondary N production lines. In other words, it lies right on the trend for secondary N production, and is somewhat below the primary plateau of $\log(N/O) \sim -1.5$. As such, its N/O ratio is at the low end of what has been measured for H II regions in spiral galaxies of comparable O abundance, and is typical of dwarf galaxies (van Zee et al. 1998). Analytic models such as Henry et al. (2000) combine both N production mechanisms to produce smooth curves of N/O versus O. RCS0327 lies on these curves near the “knee”, where the N/O ratio rapidly transitions from being independent of the oxygen abundance (“primary” production), to being highly dependent on the O abundance (“secondary” production). Comparing RCS0327 and cB58 to the numerical models of Henry et al. (2000) (their Figure 3b) suggests that both galaxies have relatively high star formation efficiencies. With a sample of two galaxies, it is premature to draw conclusions about how galaxies build up their nitrogen, but the strict N/O and O measurements we have made bode well for the future, if such work can be repeated for a larger sample.

4.6. Ionization parameter

Ionization parameters have been reported for a few other lensed galaxies, derived from the 5007/3727 diagnostic. Unfortunately, this diagnostic has a strong dependence on O abundance, so this must be input to the diagnostic. We use the 5007/3727 line fluxes reported by Hainline et al. (2009) for the Horseshoe and the Clone, assume 40% solar metallicity (Asplund system), as inferred for both from the N2 index. Converting to Anders & Grevesse (1989) abundances and using the calibration of Kewley & Dopita (2002), this corresponds to an ionization parameter of $\log U = -2.8$ for the Horseshoe and -2.7 for the Clone, without correcting for extinction. This is consistent within 0.1 dex with the values reported by Hainline et al. (2009). Teplitz et al. (2000) did not calculate an ionization parameter for cB58, so we take their line fluxes and the O abundance from Pettini et al. (2002), and find $\log U = -2.85$ for cB58 without correcting for extinction. Extinction dominates the uncertainty on this measurement, and acts to lower the ionization parameter.

These ionization parameter measurements are entirely consistent with the value measured for RCS0327 of -2.73

¹⁰ This conversion is modest (< 0.05 change in $12 + \log(O/H)$) at these metallicities.

¹¹ Teplitz et al. (2000) infer an N/O ratio that is higher by 0.5 dex, a discrepancy discussed by Pettini et al. (2002).

to -2.85 (for $A_v = 0.7$; 0.1 dex higher for $A_v = 0$). Thus, we conclude that the four lensed galaxies examined to date with this diagnostic all have very similar ionization parameters of about $\log U \sim -2.7$.

We now compare to local galaxies. The sample of Kewley et al. (2001) would be ideal for comparison, since these are IR-luminous galaxies at $z \sim 0$, but unfortunately their spectroscopy did not extend blueward to 3727 \AA . Instead, we turn to two papers which measured ionization parameters for 65 SINGS galaxies (Moustakas et al. 2010), 412 star-forming galaxies, and 120,000 galaxies from the Sloan Digital Sky Survey (Moustakas et al. 2006), using the same methodology of calculating $\log U$ as we do. The SINGS galaxies have a median and mode $\log U$ of -3.0 . The SDSS and 412 star-forming galaxies (figure 12 of Moustakas et al. 2006) have a narrow range of $-3.2 < \log U < -2.9$. The prototypical starburst galaxy M82 has $\log U = -2.9 \pm 0.07$.

Thus, the four lensed galaxies with measured ionization parameters all have the same measured value, within the uncertainties. This value, -2.7 to -2.8 , is roughly twice as high as the median for samples of lower-luminosity nearby galaxies, and is 30–60% higher than for M82. Thus, the ionization parameters of these four $z \sim 2$ star-forming galaxies are somewhat higher than local galaxies of much lower luminosity.

4.7. Electron density

In §3.9 we derived an electron density of $n_e = 252_{-28}^{+30} \text{ cm}^{-3}$ at $1.2 \times 10^4 \text{ K}$ from the $[\text{O II}]$ 3726, 3729 doublet ratio. This is currently the most precise such measurement at such high redshift. We now compare to density constraints from the literature for other lensed galaxies.

Hainline et al. (2009) measured the $[\text{S II}]$ $\lambda 6717$, $\lambda 6732$ flux ratio in two lensed galaxies. For the Clone, the result is 0.9 ± 0.1 by extracting the fluxes in each of two apertures and summing, versus 0.75 ± 0.25 by extracting all at once. For the Horseshoe, the result from the summed aperture is 1.0 ± 0.35 . Using IRAF’s *temden* at $T_e = 10^4 \text{ K}$, these ratios indicate densities of $900_{-300}^{+500} \text{ cm}^{-3}$ and $1700_{-1100}^{+11000} \text{ cm}^{-3}$ for the Clone, and $600_{-500}^{+2400} \text{ cm}^{-3}$ for the Horseshoe. Bian et al. (2010) measured a $[\text{S II}]$ flux ratio of 0.86 ± 0.2 for the sum of both apertures in J0900, which yields a density of $1100_{-600}^{+1700} \text{ cm}^{-3}$. In the rest-UV, Quider et al. (2009) measure a $\text{C III}]$ flux ratio of $f(1906)/f(1908) = 1.1 \pm 0.2$ for the Horseshoe, corresponding to a density range of $5000\text{--}25000 \text{ cm}^{-3}$, which is inconsistent with the density range measured by Hainline et al. (2009).

Thus, these literature measurements of electron density are in the range $600\text{--}5000 \text{ cm}^{-3}$, albeit with large uncertainties. The low precision of these measurements indicates a clear need for deeper spectra to better measure electron density. Nevertheless, the current measurements for the Clone, Horseshoe, and J0900 favor high electron densities, much higher than the precise value we measure for RCS0327. Thus, at present it is not clear what is a typical electron density for a star forming galaxy at these epochs. Additional high-quality measurements are urgently needed.

4.8. Location in the BPT diagram

The “BPT” diagnostic diagram of Baldwin et al. (1981) is commonly used to characterize the ionization conditions in galaxies. For RCS0327, we measure line ratios of $\log ([\text{N II}] 6583 / \text{H}\alpha) = -1.18 \pm 0.07$, and $\log (5007/\text{H}\beta) = 0.69 \pm 0.02$ for $A_v=0$ and 0.13 less than that for $A_v = 0.7$. In Figure 7 we plot RCS0327 on the BPT diagram; its high $\text{O III}/\text{H}\beta$ and extremely low $\text{N II}/\text{H}\alpha$ place it in the upper left quadrant, close to the maximal starburst line.

This is an exceptional position compared to the $z=0$ SDSS, which has only 5 galaxies in that region of the BPT diagram. However, $z=0$ IR-luminous galaxies do occupy that space: Kewley et al. (2001) have 9 galaxies with $\text{N II}/\text{H}\alpha < -1$. Since extreme star formation is rare in the local universe, these luminous star-forming galaxies may be a better basis for comparison than SDSS.

It has previously been noted that $z \gtrsim 1$ galaxies tend to be offset toward higher $5007/\text{H}\beta$ ratios in the BPT diagram (Shapley et al. 2005; Erb et al. 2006; Kriek et al. 2007). Brinchmann et al. (2008) proposed that this is caused by an elevated ionization parameter at higher redshift, and enumerated the following possible underlying causes: a top-heavy initial mass function; higher electron densities; a higher volume filling factor; or a higher escape fraction of UV photons.

Figure 7 shows that of the lensed galaxies, J0900 and the Clone show an offset similar to that of the Erb et al. (2006) stacked galaxies, while the 8 o’clock arc is considerably higher, as discussed by Finkelstein et al. (2009). By contrast, RCS0327 and cB58 are not as offset – they lie between the Erb et al. (2006) points and the $z=0$ IR-luminous galaxies.¹²

RCS0327 has a electron density ($n_e = 235_{-26}^{+28} \text{ cm}^{-3}$) that is lower than the best-fitting densities for the Clone, Horseshoe, and J0900, though those other measurements have very large uncertainties. Its measured ionization parameter (2.9 ± 0.17 for $A_v = 0.7$) is entirely consistent with measurements of the same diagnostic in the Horseshoe, Clone, and cB58. Thus, in two ways RCS0327 contradicts the picture of Brinchmann et al. (2008) for BPT behavior at $z=2$: First, though its ionization parameter is the same as the other $z=2$ galaxies, it is not as offset in the BPT diagram; second, the electron density is not high, as has been suggested to explain offsets in the BPT diagram.

Of the IR-luminous sample of Kewley et al. (2001) with $\text{N II}/\text{H}\alpha < -1$, the median electron density is $\sim 100 \text{ cm}^{-3}$. This is another case in which offsets in the BPT diagram do not appear to be caused by high density.

At present, too few $z=2$ galaxies have the high-quality spectroscopy necessary to fully map their behavior in the BPT diagram, and link offsets back to evolution in physical conditions. This will presumably change as new lensed galaxies are pursued, and as new multi-object near-IR spectrographs push down the luminosity function of the non-lensed galaxy population. That said, RCS0327 demonstrates that offsets in the BPT diagram are not driven by higher ionization parameters and densities, as has been suggested. It also demonstrates that

¹² The Horseshoe is not plotted because $\text{H}\beta$ was contaminated by a skyline (Hainline et al. 2009). CB58 was not plotted because $[\text{S II}]$ was not observed.

star-forming $z=2$ galaxies may have quite similar ionization parameters and densities to $z=0$ galaxies.

Last in our discussion of the BPT diagram, we note that RCS0327's extreme location places it as far as possible from the $z=0$ AGN locus. Thus, it is unlikely that the nebular emission of this galaxy is dominated by an AGN, though we have not ruled out a low-luminosity AGN (c.f. Greene & Ho 2007). Upcoming observations with the Chandra X-ray Observatory should test this.

5. CONCLUSIONS

The spectra published here total 1.3 hr of integration time, divided into 20, 20, and 40 minute integrations over three spectral regions. These spectra demonstrate the power of gravitational lensing to explore the physical conditions of star formation at the epoch when most of the Universe's stars formed.

For the second time in any galaxy at $z \sim 2$, and for the first in an average-metallicity galaxy, we tightly constrain the O abundance using the “direct” T_e method, thanks to the very constraining non-detection of [O III] $\lambda 4363$. We use this constraint to test the bright-line diagnostics of oxygen abundance, which are the easiest to measure, but are empirically calibrated at $z=0$ and thus incorporate assumptions about density and ionization parameter that may well be wrong at $z \sim 2$.

We find that the O abundance inferred from the N2 index (the ratio of [N II]/ $H\alpha$) agrees closely with the T_e method and has a small uncertainty. Ne3O2 also performs well, albeit with a larger uncertainty since [Ne III] is not a bright line. N2O3 and R23 depend so strongly on the extinction that we cannot definitively assess their performance in RCS0327, though they appear to work for the current best estimate of the extinction, $A_v = 0.7$. This is especially interesting because R23 fails in Lens22.3 (Yuan & Kewley 2009), the only published example of an [O III] 4363 detection at $z \sim 2$.

The O3N2 diagnostic is on the border of disagreeing with T_e in RCS0327, depending on extinction. Comparing to the N2 index, O3N2 predicts systematically lower abundances in five $z \sim 2$ lensed galaxies, dramatically so at near-solar metallicity. We suggest that O3N2 does not work in $z=2$ galaxies, perhaps due to different physical conditions compared to $z=0$ where this diagnostic is calibrated.

After all, O3N2 is effectively a location in the BPT diagram, and it has been shown, via small samples of lensed galaxies and stacked samples of unlensed galaxies, that $z=2$ galaxies are offset in the BPT diagram, with higher $5007/H\beta$, than the cloud of SDSS galaxies at $z=0$. Indeed, RCS0327 is offset in the BPT diagram compared to the SDSS and Kewley et al. (2001) galaxies, as offset as cB58 is, but not as offset as other $z=2$ galaxies.

This is particularly interesting given that the measured ionization parameter for RCS0327 is the same as has been measured in the Horseshoe, the Clone, and cB58: $\log U \sim -2.7$ to -2.8 , which is 30–60% higher than in M82.

We also tightly constrain the electron density: $n_e = 252_{-28}^{+30} \text{ cm}^{-3}$ at $1.2 \times 10^4 \text{ K}$, which is not terribly high compared to local galaxies. Thus, we conclude that it is premature to conclude that $z \sim 2$ star-forming galaxies have extremely high densities and ionization parameters, since the best-measured example, RCS0327, does not.

We measure the relative abundances of N, Ne, and Ar

compared to O. The Ne/O and Ar/O ratios are solar with uncertainties of ± 0.14 dex, which is reassuring since all these elements are alpha-process and should enrich in lockstep. We believe this to be the first time the Ne/O ratio has been measured at $z \sim 2$. The N/O ratio is one dex below the solar value, indicating that secondary N production has not yet begun in earnest. The O abundance and N/O ratio are startlingly similar to those of cB58; it is not clear whether this agreement is merely coincidental, or indicates characteristic values for star-forming galaxies at this epoch.

6. FUTURE DIRECTIONS

This is by no means the last word on RCS0327 or on diagnostic spectroscopy of lensed galaxies. The following observations should significantly increase what can be learned about the physical conditions of RCS0327. First, a direct measurement [O III] 4363, or an even stricter upper limit, should provide a more stringent test of the bright-line O abundance diagnostics. This comparison, and a host of other constraints, are limited by the current uncertainty in the measured extinction. This would be improved by a deeper integration of $H\beta/H\gamma$ or a simultaneous measurement of $H\alpha/H\beta$.

Thus far, we have considered only the spatially-integrated spectrum across the brightest portion of the arc. It will be fascinating to spatially map the physical conditions across this portion, and the fainter sections of the arc, to see how widely these physical parameters vary across the galaxy. Of course, such work requires a better lensing model, which will be enabled by pending HST observations.

Finally, we humbly remember that a single galaxy can be a maverick, and that only by repeating this work in a representative sample of lensed galaxies will the physical conditions of star formation at this epoch be confidently characterized. Larger samples will also fill in the BPT and mass-metallicity relations, to characterize the scatter in these relations and explore the reasons for the scatter.

Acknowledgments: We thank the IRTF Spex team for making public their telluric correction routine and their tool to find telluric standard stars, at <http://irtfweb.ifa.hawaii.edu/spex/>. We thank Kevin Schawinski for code to generate the SDSS contours in figure 7, which is adapted from Schawinski et al. (2010); we thank Fuyan Bian for code to generate Figure 6, which is adapted from Bian et al. (2010). JRR gratefully acknowledges the financial support and intellectual freedom of a Carnegie Fellowship.

Data presented herein were obtained at the W.M. Keck Observatory from telescope time allocated to the National Aeronautics and Space Administration through the agency's scientific partnership with the California Institute of Technology and the University of California. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. We acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

REFERENCES

- Abazajian, K. N., et al. 2009, *ApJS*, 182, 543
- Allam, S. S., Tucker, D. L., Lin, H., Diehl, H. T., Annis, J., Buckley-Geer, E. J., & Frieman, J. A. 2007, *ApJ*, 662, L51
- Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, 47, 481
- Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, *PASP*, 93, 5
- Belokurov, V., et al. 2007, *ApJ*, 671, L9
- Bian, F., et al. 2010, *ApJ* in press, arXiv:1004.4318v2
- Bouwens, R. J., et al. 2010, arXiv:1006.4360
- Brinchmann, J., Pettini, M., & Charlot, S. 2008, *MNRAS*, 385, 769
- Caputi, K. I., et al. 2007, *ApJ*, 660, 97
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245
- Chabrier, G. 2003, *PASP*, 115, 763
- Denicoló, G., Terlevich, R., & Terlevich, E. 2002, *MNRAS*, 330, 69
- Erb, D. K., Shapley, A. E., Pettini, M., Steidel, C. C., Reddy, N. A., & Adelberger, K. L. 2006, *ApJ*, 644, 813
- Finkelstein, S. L., Papovich, C., Rudnick, G., Egami, E., Le Floc'h, E., Rieke, M. J., Rigby, J. R., & Willmer, C. N. A. 2009, *ApJ*, 700, 376
- Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, *PASP*, 110, 761
- Greene, J. E., & Ho, L. C. 2007, *ApJ*, 670, 92
- Hainline, K. N., Shapley, A. E., Kornei, K. A., Pettini, M., Buckley-Geer, E., Allam, S. S., & Tucker, D. L. 2009, *ApJ*, 701, 52
- Henry, R. B. C., Edmunds, M. G., Köppen, J. 2000, *ApJ*, 541, 660
- Izotov, Y. I., Stasińska, G., Meynet, G., Guseva, N. G., & Thuan, T. X. 2006, *A&A*, 448, 955
- Kelson, D. D. 2003, *PASP*, 115, 688
- Kennicutt, R. C., Jr. 1998, *ARA&A*, 36, 189
- Kewley, L. J., & Dopita, M. A. 2002, *ApJS*, 142, 35
- Kewley, L. J., & Ellison, S. L. 2008, *ApJ*, 681, 1183
- Kewley, L. J., Heisler, C. A., Dopita, M. A., & Lumsden, S. 2001, *ApJS*, 132, 37
- Kobulnicky, H. A., & Kewley, L. J. 2004, *ApJ*, 617, 240
- Koester, B. P., Gladders, M. D., Hennawi, J. F., Sharon, K., Wuyts, E., Rigby, J. R., Bayliss, M. B., & Dahle, H. 2010, *ApJ*, 723, L73
- Kriek, M., et al. 2007, *ApJ*, 669, 776
- Le Floc'h, E., et al. 2005, *ApJ*, 632, 169
- Leitherer, C., et al. 1999, *ApJS*, 123, 3
- Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, *MNRAS*, 283, 1388
- Madau, P., Pozzetti, L., & Dickinson, M. 1998, *ApJ*, 498, 106
- Maiolino, R., et al. 2008, *A&A*, 488, 463
- Mannucci, F., et al. 2009, *MNRAS*, 398, 1915
- Marchesini, D., van Dokkum, P. G., Förster Schreiber, N. M., Franx, M., Labbé, I., & Wuyts, S. 2009, *ApJ*, 701, 1765
- Markwardt, C. B. 2009, *Astronomical Society of the Pacific Conference Series*, 411, 251
- McCall, M. L., Rybski, P. M., & Shields, G. A. 1985, *ApJS*, 57, 1
- Moustakas, J., Kennicutt, R. C., Jr., & Tremonti, C. A. 2006, *ApJ*, 642, 775
- Moustakas, J., Kennicutt, R. C., Jr., Tremonti, C. A., Dale, D. A., Smith, J.-D. T., & Calzetti, D. 2010, *ApJS*, 190, 233
- Osterbrock, D. E., Tran, H. D., & Veilleux, S. 1992, *ApJ*, 389, 305
- Osterbrock, D. E., & Ferland, G. J. 2006, *Astrophysics of gaseous nebulae and active galactic nuclei*, 2nd. ed. by D.E. Osterbrock and G.J. Ferland. Sausalito, CA: University Science Books, 2006,
- Ouchi, M., et al. 2009, *ApJ*, 706, 1136
- Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M. 2000, *ApJ*, 528, 96
- Pettini, M., Rix, S. A., Steidel, C. C., Adelberger, K. L., Hunt, M. P., & Shapley, A. E. 2002, *ApJ*, 569, 742
- Pettini, M., & Pagel, B. E. J. 2004, *MNRAS*, 348, L59
- Pilyugin, L. S. 2003, *A&A*, 399, 1003
- Pilyugin, L. S., & Thuan, T. X. 2005, *ApJ*, 631, 231
- Quider, A. M., Pettini, M., Shapley, A. E., & Steidel, C. C. 2009, *MNRAS*, 398, 1263
- Rieke, G. H., Alonso-Herrero, A., Weiner, B. J., Pérez-González, P. G., Blaylock, M., Donley, J. L., & Marcillac, D. 2009, *ApJ*, 692, 556
- Rigby, J. R., et al. 2008, *ApJ*, 675, 262
- Rubin, R. H., Ferland, G. J., Chollet, E. E., & Horstmeier, R. 2004, *ApJ*, 605, 784
- Schawinski, K., et al. 2010, *ApJ*, 711, 284
- Shapley, A. E., Coil, A. L., Ma, C.-P., & Bundy, K. 2005, *ApJ*, 635, 1006
- Shi, F., Zhao, G., & Liang, Y. C. 2007, *A&A*, 475, 409
- Siana, B., Teplitz, H. I., Chary, R.-R., Colbert, J., & Frayer, D. T. 2008, *ApJ*, 689, 59
- Smail, I., et al. 2007, *ApJ*, 654, L33
- Teplitz, H. I., et al. 2000, *ApJ*, 533, L65
- Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, *PASP*, 115, 389
- van Zee, L., Salzer, J. J., & Haynes, M. P. 1998, *ApJ*, 497, L1
- Vázquez, G. A., & Leitherer, C. 2005, *ApJ*, 621, 695
- Wuyts, E., et al. 2010, submitted to *ApJ*, arXiv:1005.2621
- Yee, H. K. C., Ellingson, E., Bechtold, J., Carlberg, R. G., & Cuillandre, J.-C. 1996, *AJ*, 111, 1783
- Yuan, T.-T., & Kewley, L. J. 2009, *ApJ*, 699, L161
- Zaritsky, D., Kennicutt, R. C., Jr., & Huchra, J. P. 1994, *ApJ*, 420, 87

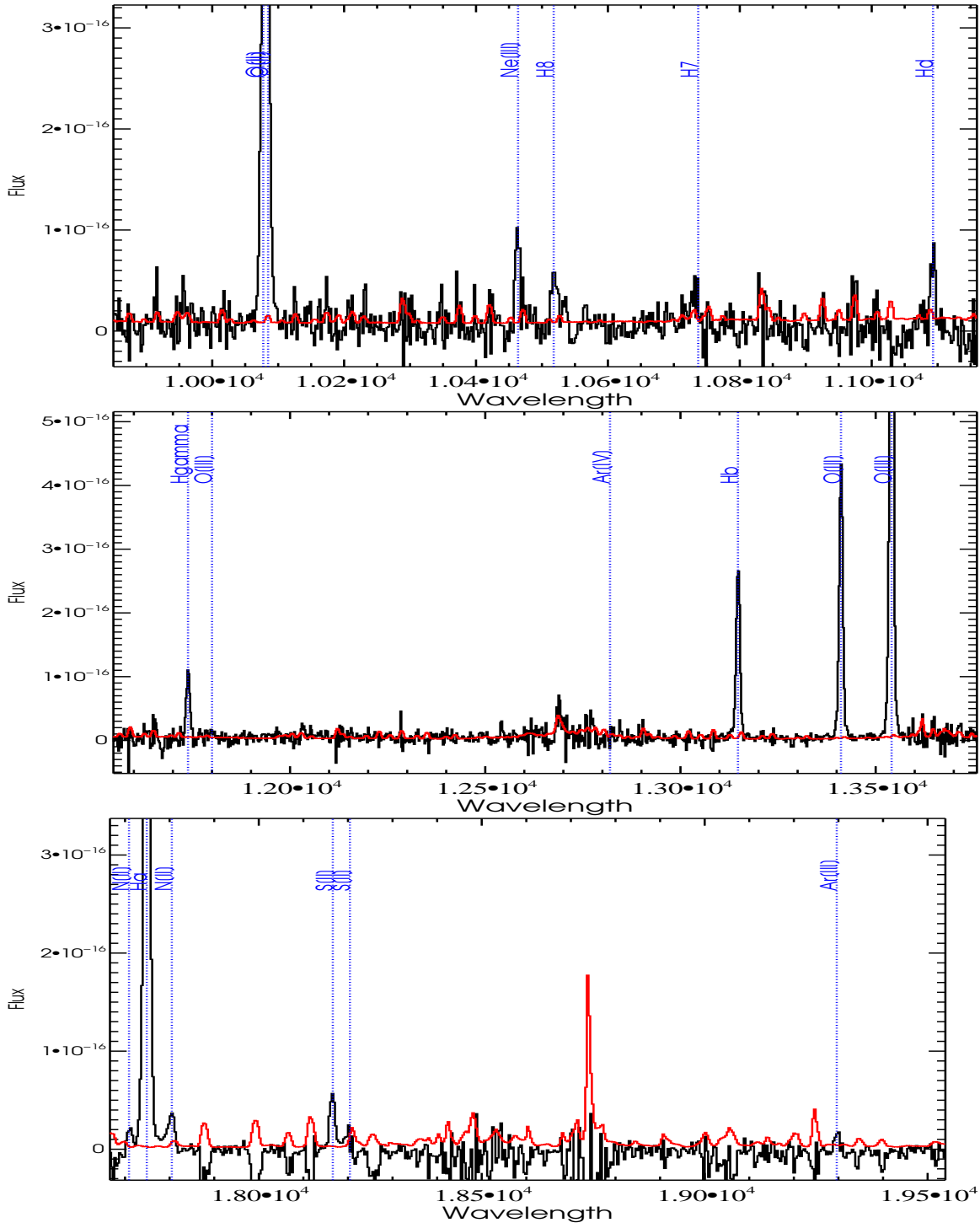


Figure 2. The NIRSPEC spectra. The fluxed spectra are plotted in black, with the 1σ error spectrum in red. The X-axis shows observed wavelength in Angstroms; the Y-axis shows observed flux in units of $\text{erg s}^{-1} \text{cm}^{-2}$. Blue labels mark detected emission lines, and lines for which we measure upper limits.

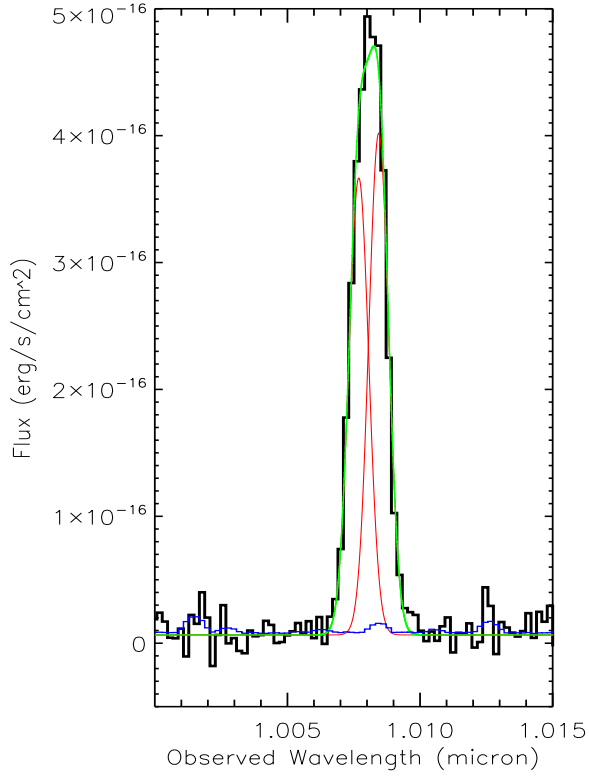


Figure 3. Two-component Gaussian fit to the [O II] 3726, 3729 doublet. Red lines show the fit to each emission line; a green line shows the summed fit. Blue shows the 1σ error spectrum.

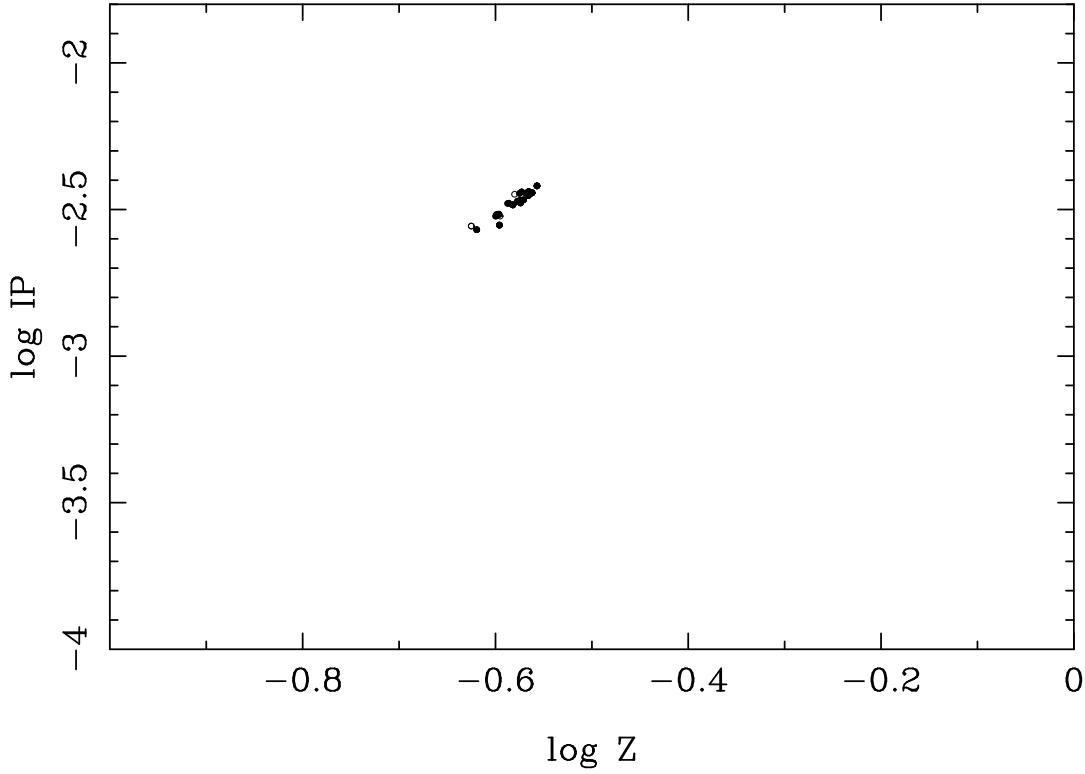


Figure 4. Starburst99 + Cloudy models, for constant star formation. A grid of models was run, varying the electron density through $\pm 1\sigma$ of the value measured in §3.9, and the starburst age. The input spectrum changes slightly due to stochastic effects. The filled circles show models with the density measured assuming $T_e = 1.2 \times 10^4$ K, and open circles show models using the density measured assuming $T_e = 10^4$ K. The measured spectral lines and the density measurement tightly constrain the ionization parameter and metallicity.

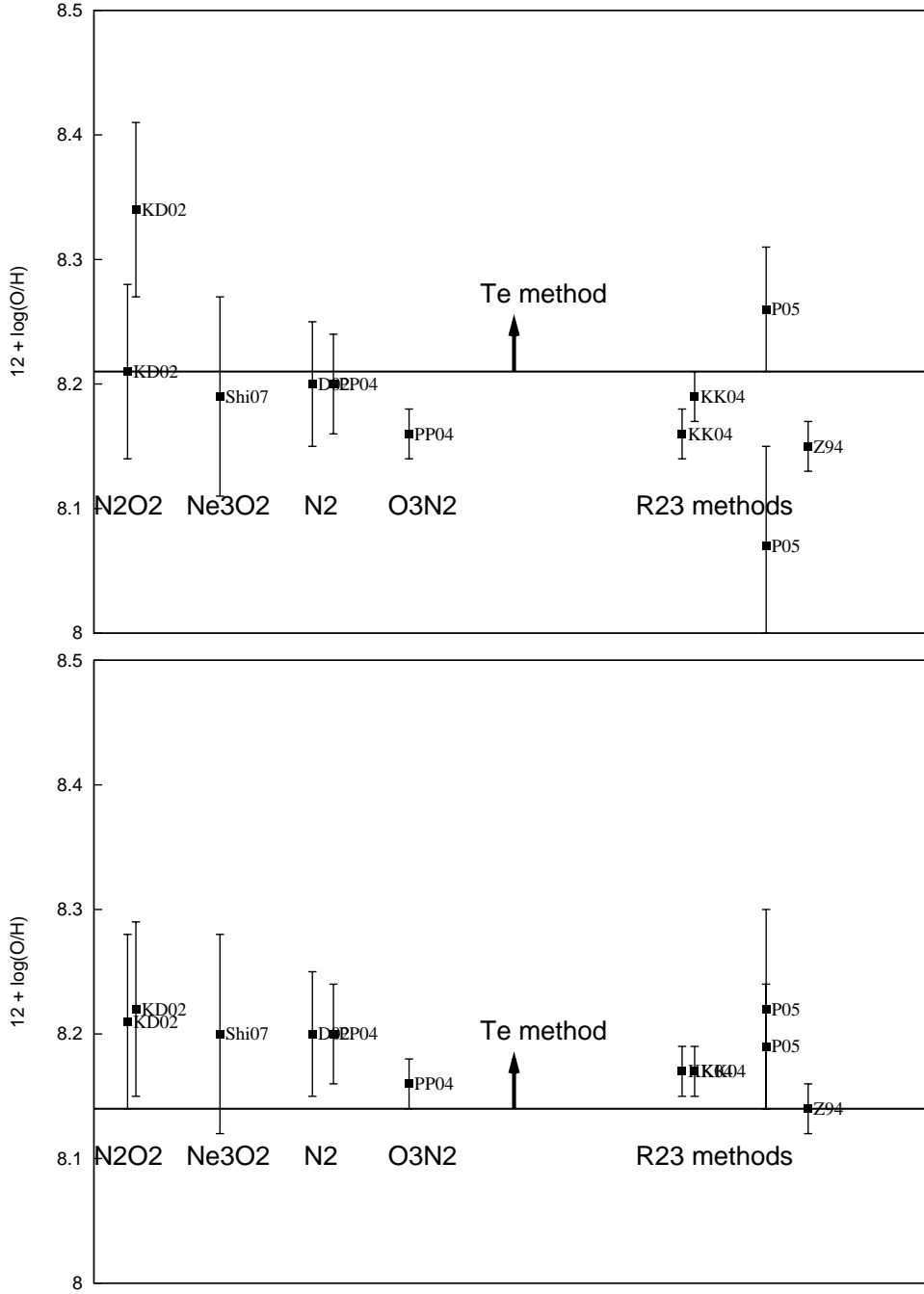


Figure 5. Comparison of oxygen abundance diagnostics for RCS0327. The top panel assumes $A_v = 0$, and the bottom panel assumes $A_v = 0.7$. The relative calibration offsets observed at $z=0$ (Kewley & Ellison 2008) have already been removed; all indices are on the relative frame of N2 in Pettini & Pagel (2004).

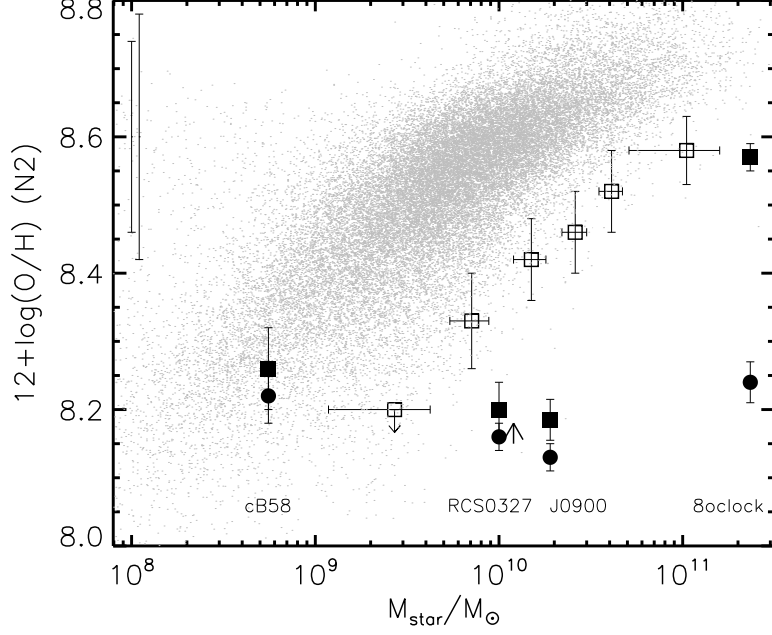


Figure 6. The Mass–Metallicity relation at $z=0$ and $z=2$. SDSS galaxies define the $z=0$ relation (*grey cloud*). The $z=2$ relation is shown by stacked spectra of unlensed $z=2$ LBGs from Erb et al. (2006) (*hollow squares*), as well as four lensed galaxies at $z\sim 2$: J0900+2234 from Bian et al. (2010); cB58 from Teplitz et al. (2000) and Siana et al. (2008); the 8 o’clock arc from Finkelstein et al. (2009); and RCS0327 from this work (*filled points*). For consistency, when authors fit stellar masses using a Salpeter IMF, we have converted to a Chabrier (2003) IMF by dividing M_* by 1.8. Squares and circles show abundances determined from the $N2/H\alpha$ and $O3N2$ calibrations of Pettini & Pagel (2004), respectively, where the $O3N2$ abundances have been brought onto the $N2/H\alpha$ relative system using the small conversion of Kewley & Ellison (2008). An arrow shows the lower limit on abundance derived from the T_e method for RCS0327. Errorbars on the data show the propagated flux uncertainty. The errorbars at upper left show the 1σ calibration uncertainties of Pettini & Pagel (2004).

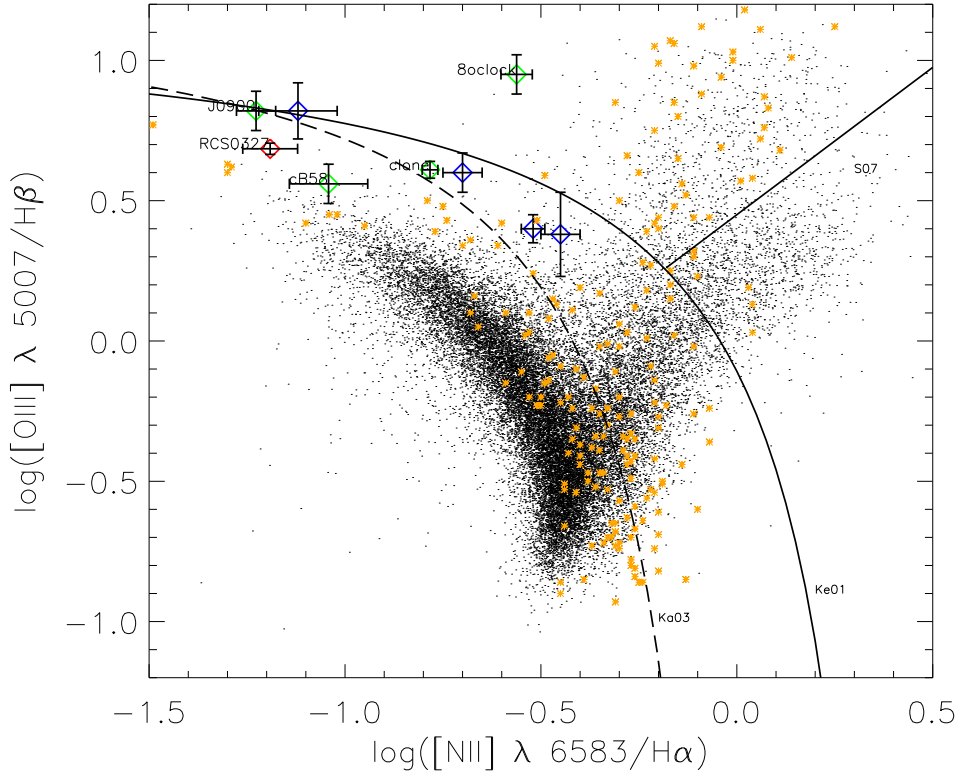


Figure 7. The BPT diagram. The $z=0$ relation is defined by the SDSS DR7 spectroscopic sample (Abazajian et al. 2009; black dots), and by the IR–bright galaxies of Kewley et al. (2001) (*orange asterisks*). Stacked samples of galaxies at $z=2$ are from Erb et al. (2006) (*blue diamonds*); lensed $z=2$ galaxies are from Bian et al. (2010), Teplitz et al. (2000), and Finkelstein et al. (2009) (*green diamonds*), and this work (*red diamond*).